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THE MERITS AND SHORTCOMINGS OF A MICHELSON TYPE INTERFEROMETER TO OBTAIN THE VERTICAL TEMPERATURE AND HUMIDITY PROFILE

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A Michelson interferometer experiment (IRIS) is under preparation for the Nimbus meteorological satellite. The major scientific objectives of this experiment are to provide global information of the vertical temperature profile, and the water vapor and ozone distribution. This information can be extracted from an analysis of the measured specific intensity I_ν within various strong and weak absorption bands (CO_2, H_2O, O_3, etc.) and windows in the thermal emission spectrum.

Instrument Requirements

The spectral range of the instrument has been chosen to cover 500 to 2000 cm^{-1} in order to meet the above criteria. Moreover, a relatively high spectral resolution equivalent to 5 cm^{-1} is required to perform the temperature and ozone analysis although slightly lower values (6-7 cm^{-1}) may be accepted for the water vapor investigation. The third and probably most difficult task to fulfill is the demand of an absolute accuracy of ±0.5% for the intensity measurement; a demand necessary for a successful temperature inversion analysis. All these rather difficult requirements can be met by a properly designed Michelson interferometer.

Michelson Interferometer Spectrometer

An essential part of the interferometer is the beamsplitter which divides the incoming radiation into two approximately equal components (Figure 1). After reflection on the fixed and moving mirrors, respectively, the two beams interfere with each other with a phase proportional to the optical path difference between both beams. The recombined components are then focused onto the detector where the intensity is recorded as a function of the path difference, δ. For monochromatic radiation, a sinusoidal signal appears while for a continuous spectrum, the superposition of many amplitudes of various frequencies takes place. The amplitudes are proportional to the intensity, I_ν, and the frequencies to the wavenumber, ν. This combined signal is called the interferogram. Neglecting constant terms, it may be expressed

$$i(\delta) = \int_{\nu_1}^{\nu_2} I(\nu) \cos(2\pi\nu\delta)\, d\nu .$$

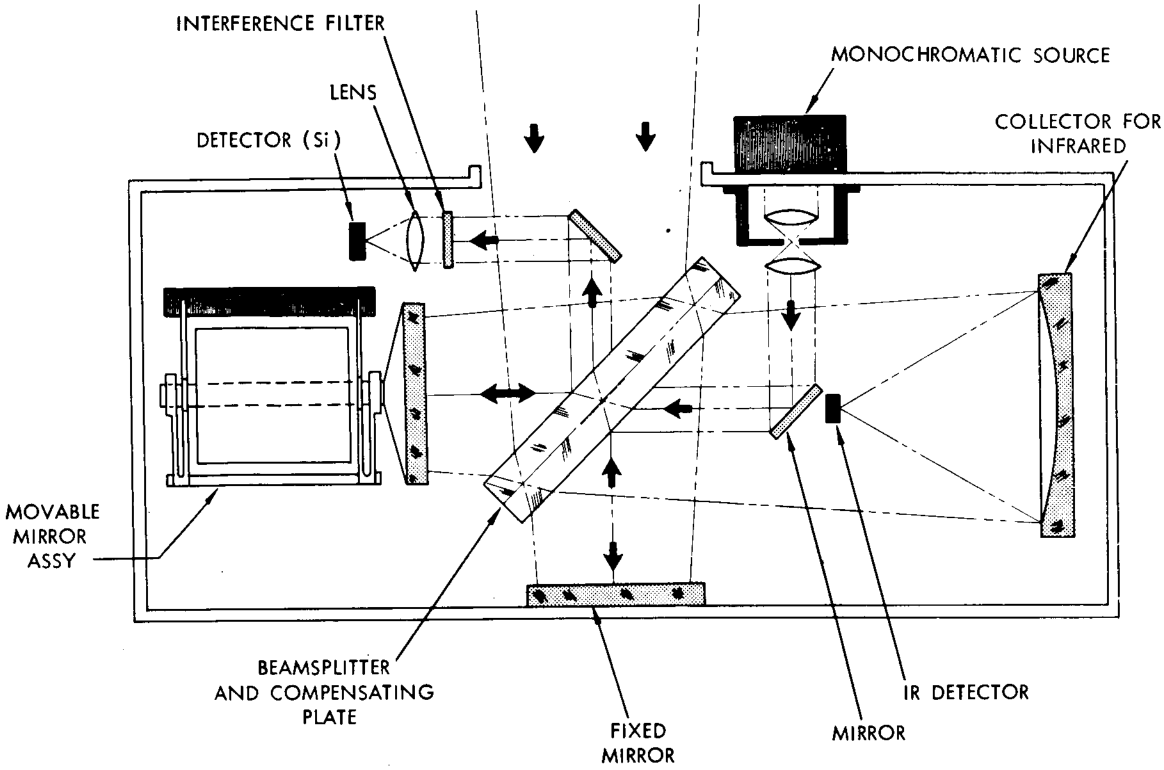

Figure 1–Schematic Diagram of Michelson Interferometer

After amplification and quantization, the signal is transmitted to the ground where the spectrum is reconstructed by applying the inverse transformation

$$I'_\nu = \int_{-\delta_{max}}^{+\delta_{max}} i(\delta) \cos (2\pi\nu\delta)\, d\delta$$

The original intensity I_ν can be recovered only within certain limits of accuracy and resolution. One limitation is the small range over which $i(\delta)$ can be recorded. Others are caused by the finite solid angle of acceptance and the noise properties of the detector.

The smallest frequency increment which can be distinguished is given by two adjacent eigenvalues of the range from $-\delta$ to $+\delta$. In other words, the spectral resolution $\nu/\Delta\nu$ is simply the number of observed periods of a particular frequency component in the interferogram. To resolve 5 cm^{-1} at 665 cm^{-1}, for example, one has to observe at least 133 periods which requires an optical path difference of 2 mm. Our instrument has a total optical path difference ($-\delta$ to $+\delta$)

of 4 mm which requires a mechanical displacement of the mirror of 2 mm. The larger path difference is necessary in practice primarily to be able to apply some smoothing (apodization) to remove side lobes of the instrument function. The interferogram of an optically and electrically well-compensated instrument is symmetrical. In such cases the a priori knowledge of symmetry may be used to obtain the same spectral resolution by recording only one-half of the interferogram, (0 to δ_m). While this is possible, uncertainties in the zero path difference position and the presence of noise make this practice difficult where a wide spectral range must be covered. Hence, we do not take advantage of the symmetry.

The solid angle of acceptance is restricted by the requirement that off axis rays striking the detector must not be greatly out of phase with the axial rays, $\Omega \leq 2\pi\Delta\nu/\nu$. In our case, this limit defines a cone of 4° half angle.

According to Shannon's theorem, the interferogram must be sampled at a rate of at least 2 samples per period of the highest frequency component of interest. We sample approximately twice that rate to remove undesired high frequency components (aliasing). The sampling interval is derived from a fringe control interferometer fed by a quasi monochromatic line from a neon source (5852.5Å).

Advantages of the Interferometric Method

The great merits of the interferometric technique can be understood from the expression of the signal-to-noise ratio obtainable in the spectral interval $\Delta\nu$

$$\left(\frac{S}{N}\right)_{\Delta\nu} = \frac{1}{\sqrt{2}}\eta D^* \sqrt{\Omega_d}\, I_\nu \,\Delta\nu \sqrt{A\Omega\tau}$$

The optical efficiency is η, the figure of merit of the detector is D^*, the solid angle under which the detector is illuminated Ω_d. I_ν is the average specific intensity within the interval $\Delta\nu$, A the collecting area, Ω the solid angle of acceptance and τ the observation time. This expression is generally applicable to interferometers, monochromators, and radiometers. The main difference existing among various types of instruments, which are otherwise comparable in performance, is primarily the $A\Omega\tau$ product.

The first advantage of the Michelson type interferometer is its multiplex property, often called Felgett advantage. Each spectral element is observed simultaneously by the detectors, $\tau_\nu = \tau$. In more conventional spectrometers (monochromators), the total observation time must be shared by N spectral elements, $\tau_\nu = \tau/N$.

The second major advantage is the large $A\Omega$ product. In the absence of slits, the collecting area can be made relatively large, 10 cm^2 in our case.

Both advantages lead to a relatively small instrument (≈8 kg) in spite of severe performance requirements.

Disadvantages of the Method

Some disadvantages and difficulties of this method may now be mentioned as well as the approach applied to overcome them.

1. The spectrum is not directly accessible but requires a Fourier transformation of the interferogram. More recent computer techniques (Cooley and Tukey 1965, Forman 1966) need less than 2 seconds to transform 4000 data points on a modern digital computer, and hence the transformation does not present a serious problem.

2. Interferometers require stability of the target radiation during the recording period of an interferogram. Scintillation, for example, can be a major source of error in ground based astronomical observations. For satellite application, the earth radiance is not expected to vary within 10 sec, although image smearing due to satellite motion may cause severe errors. For the Nimbus satellite application, image motion compensation is used to counteract the relative angular motion of the target area.

3. Compared to conventional radiometers, the tolerances of optical alignment are very critical. Rugged construction and a careful thermal design are essential.

4. The high accuracy required can only be achieved by a very large dynamic range (2000:1) in the data channel. Linearity is very important. A gain switch technique has been applied which in effect reduces the dynamic range to 256:1 with a negligible sacrifice in overall accuracy. The very few samples in the center of the interferogram which exceed one tenth of the maximum level are divided by 10 before quantization. An extra bit in each data word indicates the position of the gain switch.

Calibration

To obtain the high absolute accuracy, the instrument is periodically exposed to two calibration blackbodies of known temperature. In the satellite, one will be replaced by outer space. The other is a built-in blackbody of about 300°K. The specific intensity is then calculated from

$$I_\nu = B_\nu(1) + \left[B_\nu(2) - B_\nu(1)\right] \frac{C_\nu(T) - C_\nu(1)}{C_\nu(2) - C_\nu(1)},$$

where $B_\nu(1)$ and $B_\nu(2)$ are the intensities of the cold and warm blackbodies and $C_{\nu T}$, $C_{\nu 1}$ and $C_{\nu 2}$ the numerical result of the Fourier transformation of the target and the blackbody interferograms respectively. The required accuracy is not explicitly dependent on the instrument's responsivity or its operating temperature (250°K).

Results from Laboratory and Balloon Flights

A breadboard model of an interferometer was built and tested in the laboratory and also flown on a high altitude balloon during the spring of this year. As an example of one of the laboratory tests, a resolution check shall be shown. The instrument was exposed to the exit slit of a conventional monochromator. An expanded spectrum of the nearly monochromatic line is shown in Figure 2 where the 5 cm^{-1} resolution is clearly demonstrated. An atmospheric spectrum obtained by the breadboard model from an altitude of 31.4 km above a cloud free area is shown in Figure 3. Each curve represents the average of 3 individual spectra. The superposition demonstrates good reproducibility of the results over large

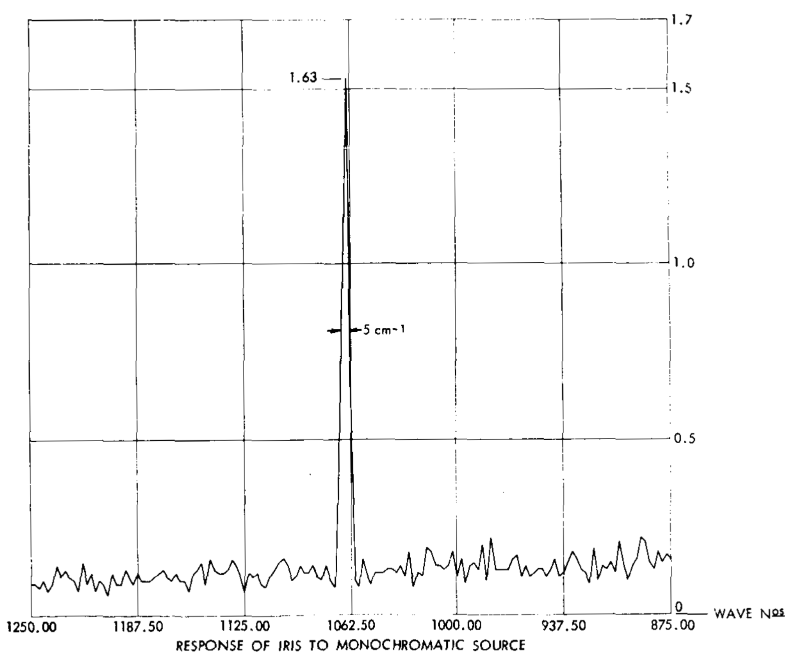

Figure 2–Response of IRIS Instrument to a Grating Monochromator Illuminated by a GLOBAR Source

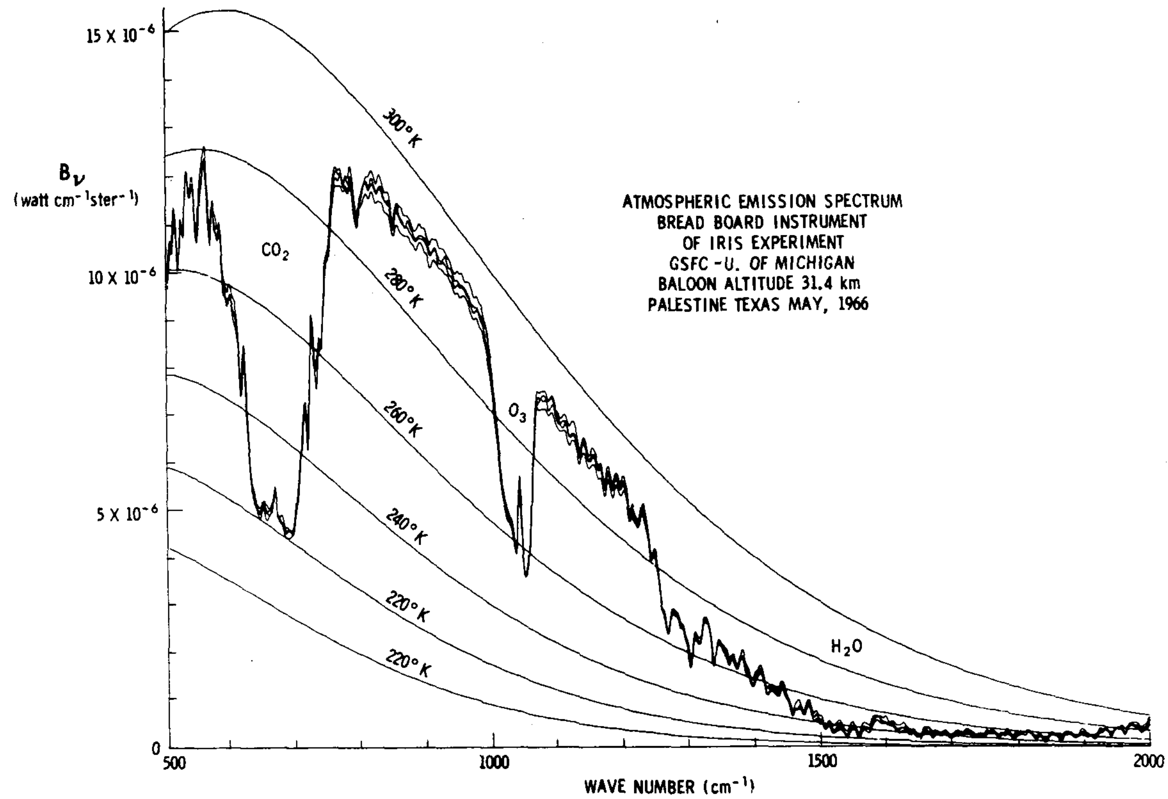

Figure 3—Four Superimposed Emission Spectra of a Clear Atmosphere Recorded by IRIS Breadboard Instrument from a High Altitude Balloon

portions of the spectrum. The gradual increase in the brightness temperature observed in the window reflects the morning rise in the surface temperature. In other parts of the spectrum, primarily towards the 2000 cm^{-1} limit, the reproducibility is only fair principally due to a limited signal-to-noise ratio. The 15μ CO_2 band and the 9.6μ O_3 band are easily recognizable. The weaker spectral features in the window can be attributed either to CO_2 or H_2O. Most lines beyond 1200 cm^{-1} can be identified with the 6.3μ water vapor band except the strong feature at 1302 cm^{-1} which is tentatively attributed to CH_4. A preliminary temperature inversion has been made by Conrath (to be published); the result is encouraging, as seen in Figure 4. Similar studies are in progress to determine water vapor and ozone distribution.

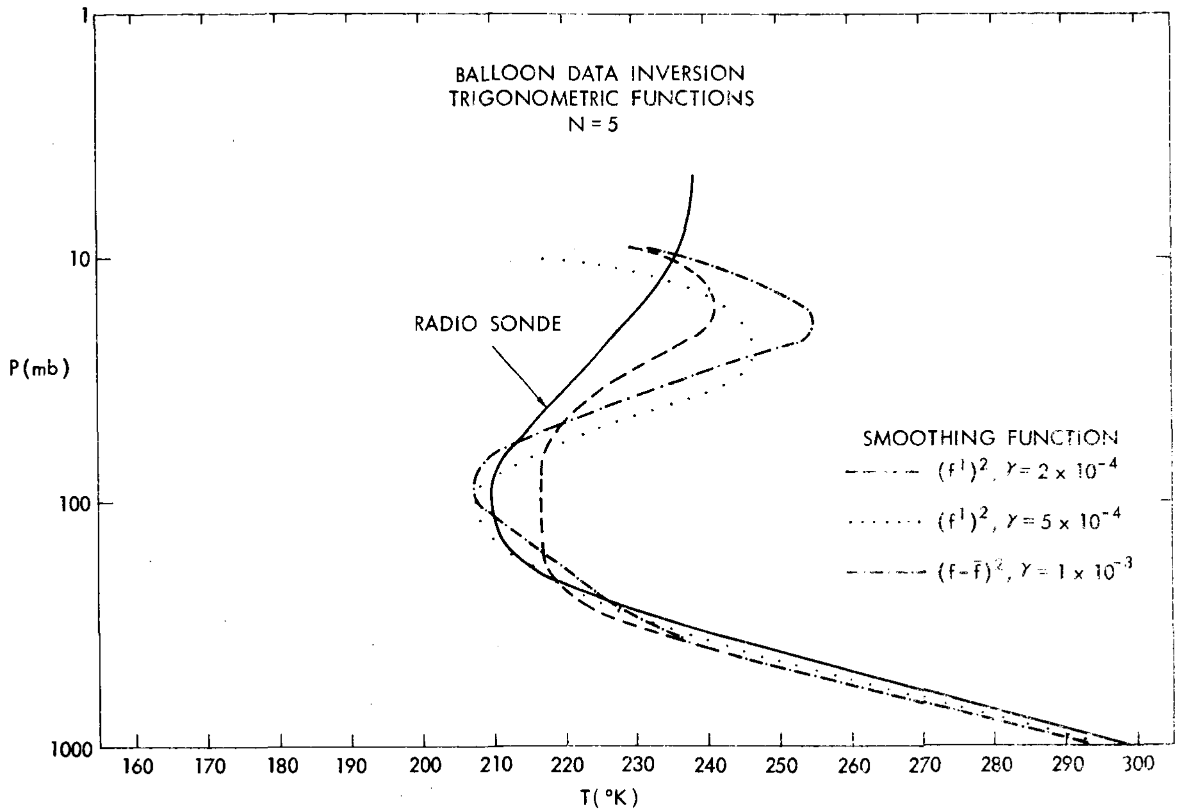

Figure 4–Comparison of Radiosonde Data with Atmospheric Temperatures Derived from the Infrared Emission Spectrum Shown in Figure 3 for Several Smoothing Functions (Conrath).

REFERENCES

1. J. W. Cooley and J. W. Tukey, Math. Computation, Vol. 19, 296 (1965).
2. M. L. Forman, Journal of Optical Society of America, Vol. 56, No. 7, 978-979 (1966).